

Neuro-Fuzzy Models to Assess Secondary Pollution Control Strategies

Reti neuro-fuzzy per la valutazione di strategie di controllo della qualità dell'aria

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Riassunto: Nel pianificare strategie di controllo della qualità dell'aria, le Autorità regionali necessitano di strumenti modellistici che consentano di valutare sia l'efficienza, sia i costi di diverse misure di riduzione delle emissioni. Il problema può essere formalizzato come un problema multi-obiettivo che integra modelli sorgente-recettore e modelli di valutazione dei costi di abbattimento degli inquinanti primari. Entrambi gli aspetti presentano elementi di complessità. In questo lavoro la relazione non lineare tra le emissioni dei precursori e le concentrazioni di inquinanti secondari è descritta per mezzo di modelli neuro-fuzzy, calibrati utilizzando i risultati delle simulazioni di lungo termine di un sistema modellistico multifase. Il caso studio preso in esame è la regione Lombardia; quest'area, caratterizzata da orografia complessa, consistenti emissioni urbane ed industriali ed una fitta rete stradale, è frequentemente interessata da episodi critici di inquinamento secondario.

Keywords: photochemical pollution control, emission reduction, multi-objective mathematical programming, neuro-fuzzy model, transport and chemical modelling system.

1. Introduction

Since last decade photochemical smog episodes have become more and more critical over Europe, mainly in Mediterranean regions, where the sun radiation and the stagnating meteorological conditions occurring in summer season play a significant role in chemical transformations of urban and industrial pollutant emissions. The cause-effect chain relations between precursors (typically nitrogen oxides (NO_x) and volatile organic compounds (VOC)) and photochemical pollutants (mainly tropospheric ozone, NO_2 , PAN and formaldehyde) are thousands and characterized by different reactive times, resulting complex and non-linear.

This property depends on the specific urban and industrial structure of the area, on the local meteorological conditions, on the contribution of regional and local emissions of photochemical smog precursors, "hot spot" areas occurring especially in Mediterranean areas and the local photochemical regimes (Sillman (1999)).

As a consequence of such complexity, the European Union suggests regulatory Agencies to define the problem at regional level in order to better interpret the air pollution situation and to define plans in terms of reductions of the emissions of ozone precursors.

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Such measures can be selected on the basis of different techniques such as the cost-benefit analysis or the cost-effectiveness analysis (Schleiniger (1999) and Streets *et al.* (2001)).

As the estimation of pollution damages often is difficult to be estimate proves unfeasible, the problem can be formalized as a multi-objective optimization (Finzi and Guariso (1992), Schöpp *et al.* (1999), Shih *et al.* (1998), Friedrich and Reis (2000), Guariso *et al.* (2004)). This approach presents the difficulty of including the complex non linear dynamics of ozone formation within the optimization problem formulation.

The source-receptor relationship can be simulated by deterministic 3D modelling systems, describing transport and chemical atmospheric phenomena. Such models require so high computing times that they are virtually unserviceable in a multi-objective mathematical program.

To get round the problem, in literature the source-receptor relationship has been described using ozone isopleths (Flagen and Seinfeld (1988), Loughlin (1998)) or with reduced form models. These last can be divided in turn into simplified photochemical models (for instance, by adopting semi empirical relations calibrated with experimental data, as in Venkatram *et al.* (1994), or by using statistical regressions on the results of very complex 3D transport-chemical models (long term simulations for Europe domain in Schöpp *et al.* (1999) and Friedrich and Reis (2000), short term simulations for Lombardia domain in Barazzetta *et al.* (2002)). The final multi-objective mathematical problem can then be solved by various techniques, including genetic algorithms, as in Loughlin (1998).

In this paper, a two-objective analysis (air quality and costs) to select effective ozone control plans is formalized.

The nonlinear relation between emission and pollution is described for Lombardia Region (Northern Italy) by neuro-fuzzy models, calibrated on long term simulations of GAMES (Volta and Finzi (in press)) photochemical modelling system.

2. Problem formulation

The ground level ozone control can be formulated as a two-objective mathematical programming problem including the effectiveness of emission reduction policies and their costs.

The air quality objective is the minimization of the seasonal accumulated ozone dose (AOT60) above the 60 ppb cut-off value for daylight hours over a grid domain. This index measures the population exposure in World Health Organization and EU Directives.

The daily cell exposure can be formalized as follows:

$$AOT60_{i,j}(d) = \sum_{h=1}^{H_d} [O3_{i,j}^h(d) - 60] \quad \text{for } O3_{i,j}^h(d) > 60ppb \quad (1)$$

where:

i, j are the cell position indexes;

d is the daily index during the reference summer season (April-September);

H_d is the number of daylight hours (during d th day), i.e. when the potential global radiation is $>50 \frac{W}{m^2}$;

$O3_{i,j}^h(d)$ is the mean ozone concentration (ppb) in (i, j) cell for h th daylight hour during d th day;
 $AOT60_{i,j}(d)$ is in $[ppb \cdot h]$

As photochemical pollution is formed from emissions of nitrogen oxides and of volatile organic compounds in the presence of sunlight, the daily cell exposure is function of meteorological parameters (that cannot be handled) and of emissions (decision variables).

As a regional authority can impose a reduction to a certain emission sector, the daily cell emissions is expressed with respect to a reference situation and split in 11 sectors according to the CORINAIR classification (EMEP/CORINAIR (1999)). So the cell AOT60 can be described stressing the emission dependance as follows:

$$AOT60_{i,j}(d) = AOT60_{i,j}(N_{i,j}^s(d) \cdot r_s^N, V_{i,j}^s(d) \cdot r_s^V) \quad (2)$$

where:

$N_{i,j}^s(d), V_{i,j}^s(d)$ are respectively the daily cell NO_x and VOC emissions in the reference case for sector s ;
 $\Xi(r_s^N, r_s^V)_{s=1,\dots,11}$ is the decision variable set, namely the percentage of sector precursor emission reductions (respectively for NO_x and VOC).

The formalization of source-receptor function, explaining complex local and regional factors (transport processes, atmospheric chemical non linear behavior, anthropogenic and biogenic emission mixture), is described in the next section.

The air quality objective, minimizing the seasonal domain population ozone exposure (POE), is:

$$\min_{\Xi}(POE) = \min_{\Xi} \sum_{\forall i,j} \sum_{d=1}^D [p_{i,j} AOT60_{i,j}(d)] \quad (3)$$

where $p_{i,j}$ is the population density in (i, j) th cell and D is the amount of the summer days.

The second objective of the ozone planning is the minimization of precursor (NO_x and VOC) emission reduction costs:

$$\min_{\Xi}(Costs) = \min_{\Xi} \sum_{s=1}^{11} (N^s \cdot r_s^N \cdot c_s^N(r_s^N) + V^s \cdot r_s^V \cdot c_s^V(r_s^V)) \quad (4)$$

with the constraints:

$$0 \leq r_s^N \leq R_s^N \quad (5)$$

$$0 \leq r_s^V \leq R_s^V \quad (6)$$

where:

$c_s^N(r_s^N), c_s^V(r_s^V)$ are functions giving the unit costs related to NO_x and VOC emission reduction;

N^s, V^s are the seasonal domain NO_x and VOC emissions in the reference case;

R_s^N, R_s^V are the maximum feasible reductions allowed by the available technologies.

3. Pollutant-precursor models for Lombardia Region

The precursors-AOT60 relationship (Eq. 2) remains to be described. It could be performed by deterministic 3D modelling systems, but they require so high computing times that they are virtually unserviceable in an operational research procedure. In this section neuro-fuzzy precursor-ozone models, tuned by deterministic 3D modelling system simulations, are suggested and implemented for Lombardia Region (Figure 1).

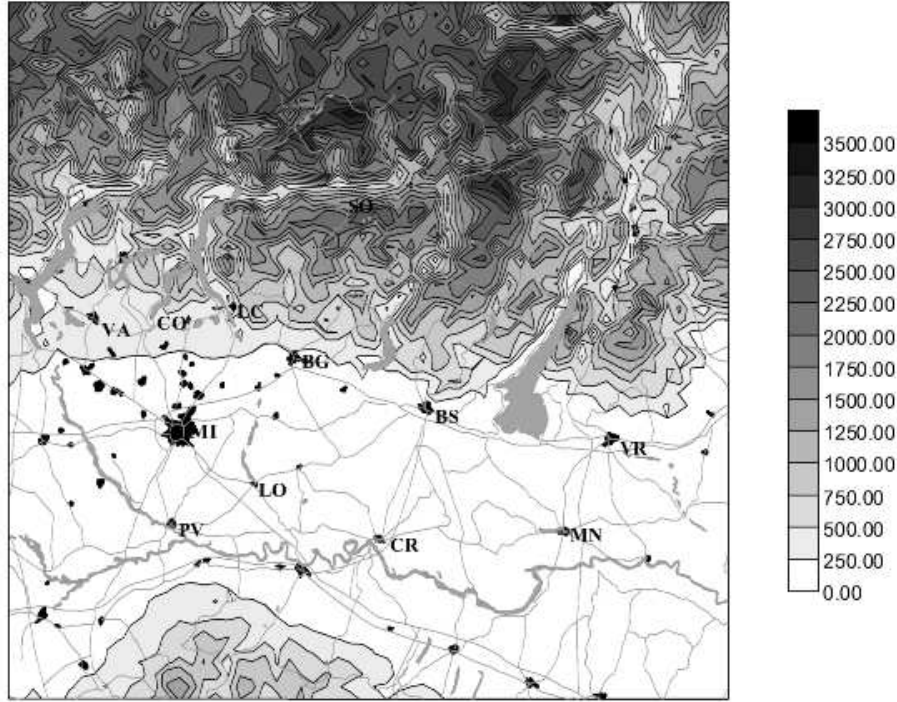


Figure 1: The simulation domain orography (m a.s.l.).

GAMES long term simulations Ground level ozone concentrations and exposure have been simulated implementing the GAMES modelling system consisting of some main modules (Figure 2).

The photochemical model TCAM (Decanini and Volta (2003)) is an eulerian three-dimensional model. It solves, time by time, by means of adequate numerical algorithms, for each cell and pollutant species, the mass balance equation:

$$\begin{aligned}
 \left[\frac{\partial c_i}{\partial t} \right] = & - \left(\frac{\partial (u_x c_i)}{\partial x} + \frac{\partial (u_y c_i)}{\partial y} + \frac{\partial (u_z c_i)}{\partial z} \right) \\
 & + \frac{\partial}{\partial x} \left(K_x \frac{\partial c_i}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial c_i}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial c_i}{\partial z} \right) \\
 & + S_i + E_i - D_i
 \end{aligned} \tag{7}$$

where:

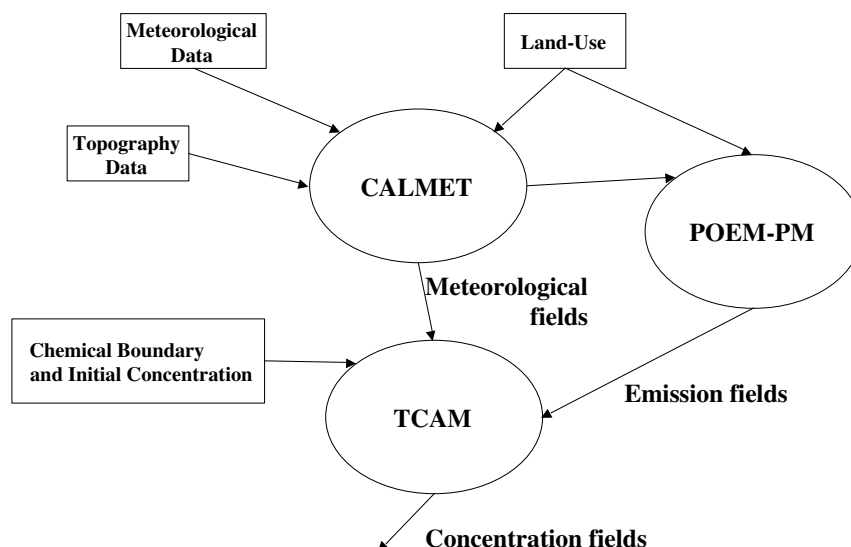


Figure 2: The GAMES modelling system

c_i is the concentration of the i -th species;
 u_x, u_y, u_z are the components of mean wind speed;
 K_x, K_y, K_z are the turbulent diffusion coefficients;
 S_i is the chemical production and reduction term;
 E_i is the emission term;
 D_i is the deposition term.

The TCAM implements simplified chemical mechanisms based on both lumped molecule (SAPRC90 and SAPRC97, Carter *et al.* (1997)) and lumped structure approaches (CB4, Gery *et al.* (1988)). The meteorological pre-processor CALMET (Scire *et al.* (1990)) provides to the TCAM the 3D meteorological fields of wind, temperature and turbulence. The emission data feeding TCAM are provided by the emission processor POEMPM (Carnevale *et al.* (in press)), specifically designed to produce present and alternative emission scenarios.

The modelling system has been performed over the whole of Lombardia Region, a densely inhabited and industrialized area located in the Po Valley (Northern Italy) which is regularly affected by high ozone levels during summer months. The area is characterized by a VOC-limited atmospheric chemistry in the plain, suggesting that pollution control measures should first aim at a reduction of VOC emissions, while the mountain region follows the NO_x -limited photochemical regime, claiming for NO_x emission reductions (Gabusi and Volta (2005)).

The domain (240 x 232 km²) has been horizontally subdivided into 60 x 58 cells, with a resolution of 4x4 km² each. Vertical domain extends up to 3900m a.s.l., subdivided into 11 layers of growing thickness.

Simulations have been performed for 1996 summer season (from April to September), assuming initial and boundary conditions from a nesting procedure of the European scale EMEP Lagrangian Photo-oxidant Model (EMEP/CORINAIR (1999)).

Implementing the actual meteorology, emission and border conditions of that period,

the base case simulation has been performed, supplying pollutant hourly concentration fields. The comparison with the actual values measured during the simulation period meets US EPA recommendations and recent European Directive on modelling validation (Pirovano *et al.* (2004), Gabusi and Volta (2005)). The computation of such a simulation takes few days and this explains why GAMES cannot be directly used by an optimization procedure that would processing hundreds of model runs.

Keeping the meteorology and border conditions of simulation period as constant and arbitrarily reducing ozone precursor emissions of a certain ratio, seven alternative scenarios (reducing or increasing NO_x or/and VOC emissions) have been performed and collected for the calibration of simplified source-receptor models described in the following section.

Neuro-fuzzy source-receptor models Simplified source-receptor models have been set up by means of neuro-fuzzy architecture. In neuro-fuzzy systems, neural networks are used to tune the membership functions of the fuzzy system and to automatically extract fuzzy rules from numerical data (Shing and Jang (1993)). In this work, a four-layer neuro-fuzzy network has been considered. The nodes of the first layer represent the crisp inputs. The activation functions of the second layer nodes act as membership functions. Each neuron of the third layer acts as a rule node so that this layer provides the fuzzy rule base. The output of this layer determines the activation level at the output memberships. As ordinary neural nets, the neuro-fuzzy one learns from a training data set, tuning membership functions and rules.

One neuro-fuzzy model has been identified for each domain cell. The input data are the cell maximum daily temperature and the daily VOC and NO_x emissions estimated for an area around the cell within an radius of 4 to 10 km. The output data are the daily AOT60 estimation performed by the GAMES system. The neuro-fuzzy models, running in simulation mode, estimate the daily cell exposure from which the AOT60 seasonal values are provided according to Equation 2.

The tuning and validation data series are selected processing the eight performed GAMES simulations. Each simulation covers the 1996 summer season, namely 183 days, so the available data correspond to 183x8 days. The validation set has been yielded selecting, from the simulation pattern, groups of data that are representative of different emission scenarios and meteorological conditions, for a total amount of a entire season, i.e. 183 samples. The identification pattern includes the remaining 183x7 samples.

4. Neuro-fuzzy model performances

The performances of the simplified source-receptor models, evaluated on validation data set, are assessed in terms of correlation between neuro-fuzzy models and GAMES results. Figures 3, 4 and 5 show neuro-fuzzy models vs. GAMES simulations, for three cell groups, respectively below 200m a.s.l., between 200m a.s.l. and 700m a.s.l. and above 700m a.s.l..

The trend lines and correlations of the scatter diagrams show that the neuro-fuzzy models perform high capability to reproduce the nonlinear source-receptor relationship with some remarks for the three elevation levers. In the plain, corresponding to the most pollutant emitting part of the domain, the neuro-fuzzy model underestimate the exposure about 5-10% (Figure 6).

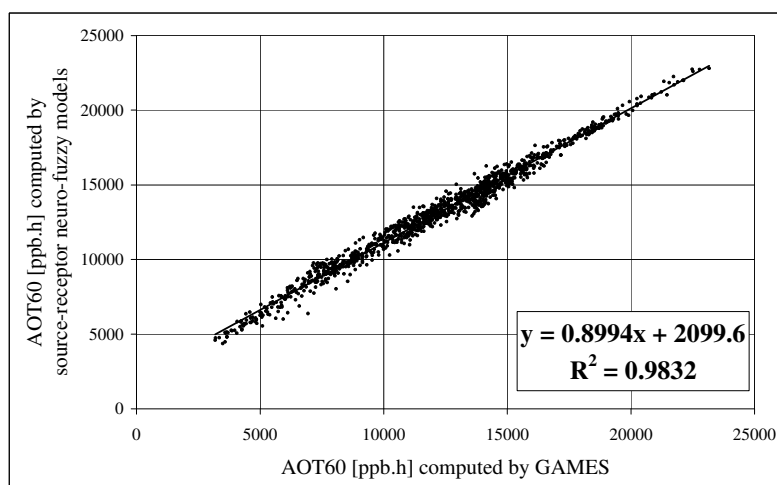


Figure 3: GAMES versus neuro-fuzzy AOT60 estimation for validation data set (cells below 200m a.s.l.).

The foothill area is better described and the error is limited to about $\pm 4\%$ in the worst cases. The Alps region AOT60 are overestimate by the the simplified pollutant-precursor models.

As the three areas are characterized by different ozone accumulation processes and photochemical regimes, these results indicate that the neuro-fuzzy models

- perform good AOT60 estimation for all emissions, transport and photochemical conditions;
- have high capability in describing Milan ozone plume attracted by the breezes towards the foothill;
- are biased by VOC emissions: the VOC-limited region (the plain) is characterized by AOT60 underestimation, on the contrary the AOT60 computed for Alps area (NO_x - limited) are overestimate.

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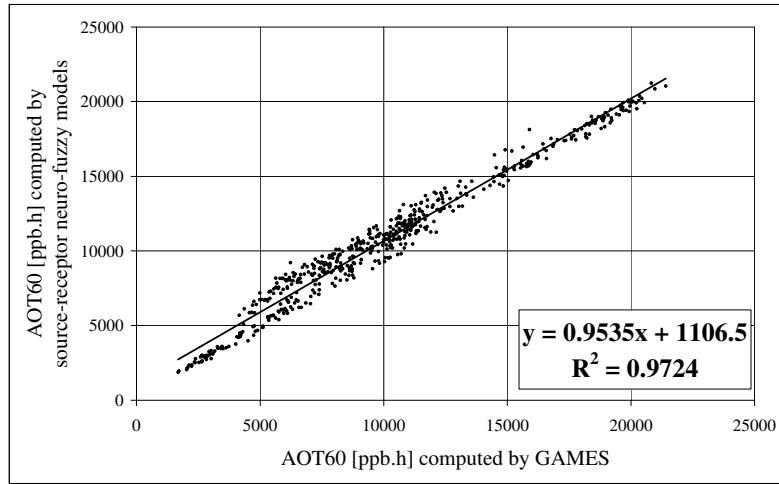


Figure 4: GAMES versus neuro-fuzzy AOT60 estimation for validation data set (cells between 200m a.s.l. and 700m a.s.l.).

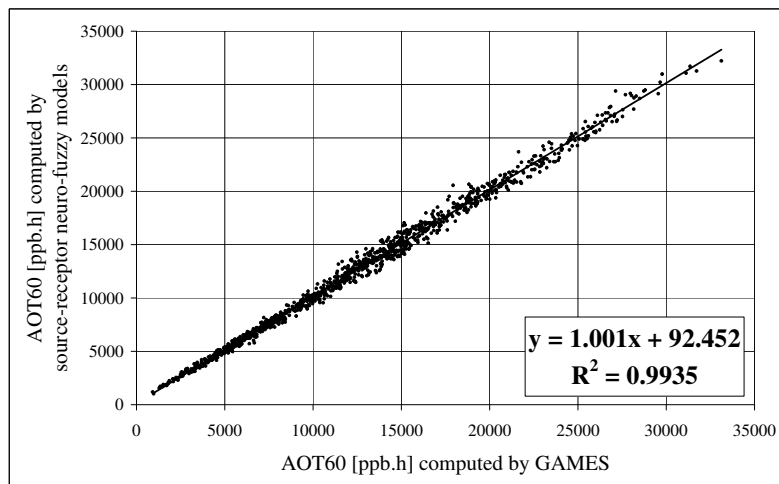


Figure 5: GAMES versus neuro-fuzzy AOT60 estimation for validation data set (cells above 700m a.s.l.).

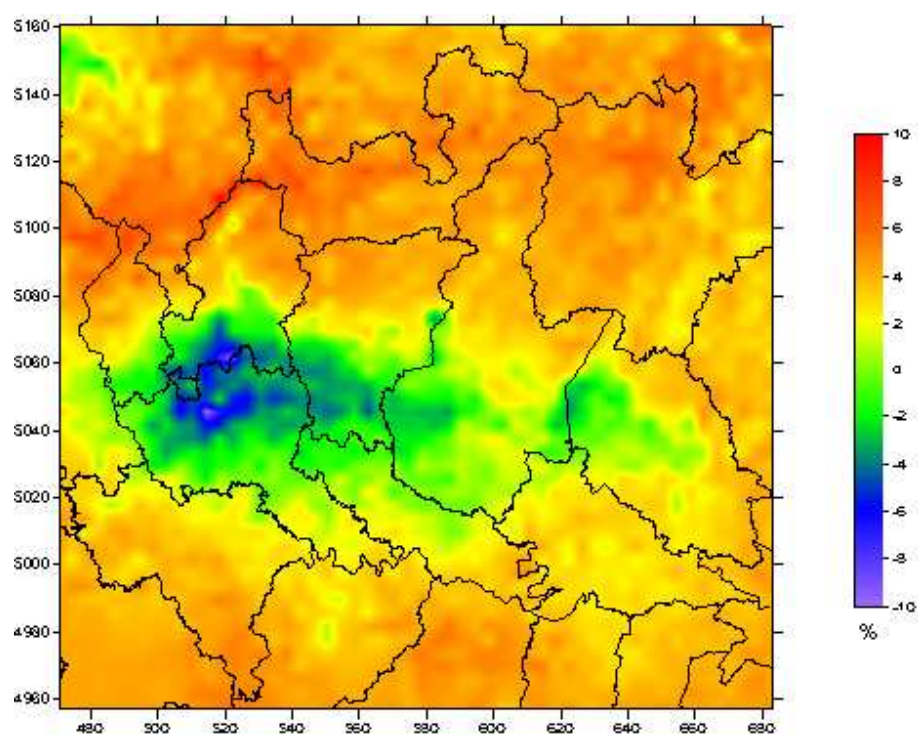


Figure 6: Neuro-fuzzy model AOT60 estimation error (%) for validation period